Assessment of Air Quality and Related Values in Shenandoah National Park

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The National Park Service (NPS) is responsible for preserving and protecting air quality and "air quality related values" in the National Park System by ensuring compliance with the requirements of the Clean Air Act, the National Park Service Organic Act, and other pertinent laws, regulations, and policies. This report focuses on the estimated historical, current, and projected future conditions of air quality, acidic deposition, and known air quality related values in Shenandoah National Park—visibility, streams, fish, aquatic insects, soils, and vegetation—and the human-made air pollutants that most affect them.

This technical document was peer-reviewed by internal and external scientists.

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AERP	Aquatic Effects Research Program
Al	Aluminum
ANC	Acid neutralizing capacity
AQRV	Air quality related value
ARD	Air Resources Division
ASTRAP	Advanced Statistical Trajectory Regional Air Pollution model
BART	Best Available Retrofit Technology
BEA	Bureau of Economic Analysis
C	Carbon
Ca	Calcium
CAA	Clean Air Act
CAAA	Clean Air Act Amendments
CARB	California Air Resources Board
CASTNet	Clean Air Status and Trends Network
CEC	Cation exchange capacity
Cl	Chloride
CIRA	Cooperative Institute for Research in the Atmosphere
CO	Carbon monoxide
CPOM	Coarse particulate organic matter
DDF	Dry deposition factor
DOC	Dissolved organic carbon
DOI	U.S. Department of the Interior
DOM	Dissolved organic matter
dv	Deciview
EGU	Electric generating unit
EPA	U.S. Environmental Protection Agency
EPT	Ephemeroptera-Plecoptera-Trichoptera
FIA	Forest Inventory Analysis
FISH	Fish in Sensitive Habitats Project
FLM	Federal Land Manager
FMP	Fisheries Management Plan
FPOM	Fine particulate organic matter
GIS	Geographic Information System
GPRA	Government Performance and Results Act
GRSM	Great Smoky Mountains National Park
HAP	Hazardous Air Pollutant
HBEF	Hubbard Brook Experimental Forest
HDDV	Heavy Duty Diesel Vehicle
IFS	Integrated Forest Study
IMPROVE	Interagency Monitoring of Protected Visual Environments Program
IPM	Integrated Planning Model
LAC	Light absorbing carbon
LTEMS	Long-Term Ecological Monitoring System
L_{VOC}	Average simulated VOC loss due to photochemistry
MACA	Mammoth Cave National Park

MAGIC	Model of Acidification of Groundwater in Catchments
MAQSIP	Multiscale Air Quality Simulation Platform model
MOU	Memorandum of Understanding
MVCP	Maximum VOC capacity point, the point at which further addition of VOCs reduced ozone concentration
N	Nitrogen
NAAQS	National ambient air quality standards
NADP	National Atmospheric Deposition Program
NADP/NTN	National Atmospheric Deposition Program/National Trends Network
NAPAP	National Acid Precipitation Assessment Program
NAS	National Academy of Sciences
NEI	National Emissions Inventory
NH_3	Ammonia
NH_4	Ammonium
NO_2	Nitrogen dioxide
NO_3	Nitrate
NO_x	Nitrogen oxides
NO_y	Reactive oxides of nitrogen
NPS	National Park Service
NWS	National Weather Service
O_3	Ozone
OTC	Ozone Transport Commission
PAN	Peroxyacetylnitrate
P_{O3}	Mean daily total ozone production through photochemical reactions
PO_4	Phosphate
POM	Particulate organic matter
ppb	Parts per billion
ppbv	Parts per billion by volume
ppm	Parts per million
PSD	Prevention of significant deterioration
RADM	Regional Acid Deposition Model
RHR	Regional Haze Rule
S	Sulfur
SAMAB	Southern Appalachian Man and the Biosphere program
SAMI	Southern Appalachian Mountains Initiative
SBC	Sum of base cations
SHEN	Shenandoah National Park
SIP	State Implementation Plan
SKT	Seasonal Kendal Test
SO_2	Sulfur dioxide
SO_4	Sulfate
SO_x	Sulfur oxide
SUM06	Sum of all hourly ozone concentrations that are greater than or equal to 0.06 parts per million
SVR	Standard visual range
SWAS	Shenandoah Watershed Study
TMDL	Total maximum daily load

USDA	U.S. Department of Agriculture
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
VDGIF	Virginia Department of Game and Inland Fisheries
VMT	Vehicle miles traveled
VOCs	Volatile organic compounds
VPOP	Ozone production per unit of VOC consumed
VR	Visual range
VTSSS	Virginia Trout Stream Sensitivity Study
W126	Sum of all hourly ozone concentrations, where each is weighted by a function that gives greater emphasis to the higher concentrations

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EXECUTIVE SUMMARY

Introduction

Shenandoah National Park overlies the crest of the northern Blue Ridge Mountains of Virginia. The park has one of the most comprehensive air quality monitoring and research programs of all national parks and wilderness areas that are afforded special protection under the Clean Air Act. Under the Clean Air Act (as amended), the Assistant Secretary for Fish, Wildlife and Parks (acting through the park Superintendent) has an "affirmative responsibility" to protect air quality related values from the adverse effects of human-made air pollution.

The park's air-related science program has emphasized particulate matter, gaseous pollutants, acidic deposition, visibility, and the acid-base status of streams. Over 20 years of monitoring and research show that, despite some recent improvements, the park's sensitive scenic and aquatic resources remain degraded by human-made air pollution. Furthermore, the park's air quality does not currently meet the 8-hour ground-level ozone standard set by the U.S. Environmental Protection Agency to protect public health and welfare.

In the late 1990s, park managers determined the need for a comprehensive, state-of-the-science assessment of the park's air quality and related values in support of air-related regional, state, and park planning, policy-making, permit review, and scientific and outreach activities. This report provides that assessment as well as key resource information. The National Park Service assembled a team of scientists to evaluate the estimated historic, current, and projected future status of air quality and air pollution effects on sensitive resources in the park. This assessment addresses the park's known air quality related values, including visibility, vegetation, soils, streamwater chemistry, fish, and aquatic insects, as well as the human-made air pollutants that most affect them. This report also summarizes pertinent national and park-specific laws and policies, and describes the park's current and estimated historic air quality and resource conditions. It synthesizes knowledge on the visibility and ecological effects of atmospheric pollutants, and documents park-specific critical load ranges for the effects of sulfur deposition on surface waters and ground-level ozone on tree growth, forest growth, and species composition. It also projects future air quality, acidic deposition, and resource conditions and recovery, assuming implementation of four emissions control scenarios.

The atmospheric and deposition modeling described herein was conducted using the Extended Regional Acid Deposition Model to: (1) determine principal emissions source subregions, known as airsheds, responsible for the majority of acidic deposition and sulfate haze affecting the park; (2) apportion the relative contribution of the airshed emissions, as a function of distance from the park, to the acidic deposition and sulfate air concentrations in the park; (3) define the top-ranked source subregions within the airsheds responsible for the largest fraction of acidic deposition and sulfate air concentrations affecting the park; (4) illustrate the relative contributions of 13 eastern states to acidic deposition and sulfate haze in the park; and (5) project future air quality and acidic deposition in response to the emissions control scenarios considered. Park and regional monitoring data were used to characterize recent and current conditions and to evaluate model performance. Four emissions control scenarios were considered. Scenarios 1 and 2 were based on emissions regulations required by the 1990 Clean Air Act Amendments and projected to 2010 and 2020, respectively. Scenario 3 was based on more stringent controls on sulfur dioxide and nitrogen oxides emissions from electric utilities sources than were mandated by the 1990 Clean Air Act Amendments. Scenario 4 was based on the same emissions controls on electric utilities sources as required by Scenario 3, plus more stringent controls on emissions from industrial point sources and mobile sources than required by the 1990 Clean Air Act Amendments.

Dose-response calculations and simulation modeling were used to estimate potential future changes in the extent of damage to visibility, aquatic, and forest resources in Shenandoah National Park in response to Scenarios 1 through 4. The Model of Acidification of Groundwater in Catchments was used to simulate aquatic ecosystem effects and determine ranges of critical sulfur deposition loadings. The TREGRO model was used to simulate the isolated effects of ground-level ozone on tree growth. The ZELIG gap succession model was used to simulate the isolated effects of ozone on forest stand composition and growth. Future visibility conditions were projected for each of the emissions control scenarios on the basis of expected reductions in fine sulfate particle concentrations in the atmosphere and the known contribution of each particle type to light extinction. These analyses augmented a broader literature review pertinent to the effects of human-made air pollutants on visibility and aquatic and terrestrial ecosystems.

Overall, this assessment found that implementation of emissions controls, especially Scenarios 3 and 4, would be expected to make progress toward, but not fully restore, the park's estimated natural visibility conditions and acid-base chemistry of the most sensitive aquatic ecosystems. Full implementation of the 1990 Clean Air Act Amendments (Scenario 2) should also make substantial progress toward protecting park forests from the isolated effects of ground-level ozone. In addition, thirteen eastern states and several source subregions were identified that can contribute the most toward restoring and protecting air quality and related values in Shenandoah National Park. The following is a summary of key assessment findings by major topic.

Detailed Summary of Assessment Findings

Emissions and Air Pollutant Transport

- Major emissions source subregions impacting the park are found in the Ohio River Valley, northeastern West Virginia, southwestern Pennsylvania, and central and eastern Virginia.

- In descending order of importance, Ohio, Virginia, West Virginia, Pennsylvania, and Kentucky comprise the top five of thirteen key states causing sulfate air concentration and haze impacts at the park. West Virginia, Ohio, Virginia, Pennsylvania, and Kentucky comprise the top five states causing sulfur deposition impacts at the park. Virginia, West Virginia, Ohio, Pennsylvania, and North Carolina comprise the top five states causing oxidized nitrogen deposition impacts at the park.

- Emission sources within about 200 kilometers (125 miles) cause greater visibility and acidic deposition impacts at the park**,** *on a per ton basis*, than more distant sources.

- Because of the non-linear production of sulfur pollutants during transport, changes in sulfur dioxide emissions do not translate into proportionate changes in sulfate air concentrations or sulfur deposition. These non-linearity effects are more pronounced for haze than deposition, especially at higher sulfate air concentrations.

- For five air pollutants (sulfur dioxide, nitrogen oxides, volatile organic compounds, carbon monoxide, coarse particulate matter), in-park emissions comprise less than 1% of total human-made emissions from the eight counties encompassing the park.

Ambient Air Quality and Acidic Deposition

The park has among the highest monitored concentrations of airborne sulfate particles, acidic deposition, and ground-level ozone of all national parks.

Ground-level Ozone

- Many experts consider 25 parts per million-hour (ppm-hr SUM06) to be an important ozone exposure threshold above which vegetation begins to show effects. The mean and maximum ozone exposures at Big Meadows were 47 ppm-hr and 87 ppm-hr, respectively, during the period 1990-2000.

- The park's air quality from 1997 through 2001 did not meet the 8-hour ground-level ozone standard set in 1997 by the U.S. Environmental Protection Agency to protect public health and welfare.

Acidic Deposition

- Estimated total (wet + dry) annual deposition values at Big Meadows are currently about 13 kg/ha/yr for sulfur and 8 kg/ha/yr for nitrogen.

- The park does not routinely monitor cloud and fog deposition, but limited in-park research suggests its contribution toward the total deposition budget is relatively small compared to higher elevation sites such as Whitetop Mountain, Virginia.

- Concentrations of sulfur in wet deposition have shown a decreasing trend over the past 15 to 20 years at Big Meadows, North Fork Dry Run and White Oak Run.

- Concentrations of nitrogen in wet deposition have shown evidence of some decline over the past 15 to 20 years at North Fork Dry Run and White Oak Run, but not at Big Meadows.

Visibility Status and Trends

Visibility has been degraded in the park, potentially detracting from visitor enjoyment of numerous vistas accessible from Skyline Drive (a Virginia State Scenic Highway), the Appalachian National Scenic Trail, and other trails and points in the park.

- Current annual average visual range is about 20% of the park's estimated natural visual range of approximately 185 kilometers (115 miles).

- Current annual average haziness is about three times greater than the park's estimated natural haziness of about 7.5 deciviews.

- Seasonal variability in visibility is driven primarily by changes in the atmospheric concentration of ammonium sulfate, and poorest visibility occurs in summer.

- Even the park's clearest 20% of days, which occur mainly in winter, are degraded by human-made particulate matter. The fine mass budget on these clearest days includes about 51% sulfates and 12% nitrates.

- Although the clearest 20% of days showed no consistent trend for March 1988 through February 2000, the haziest 20% showed a moderately improving trend.

Terrestrial Ecosystem Status and Trends

Ground-level Ozone

Ground-level ozone is considered to be a long-term, potentially debilitating stress to the park's ozone-sensitive vegetation that can interact with other, potentially exacerbating stresses such as drought, insects, and diseases. This assessment focuses on the isolated effects of ozone on trees and forests. Ground-level ozone also causes visible foliar damage to several plant species in the park, including but not limited to milkweed, black cherry, yellow poplar, and white ash. However, little is known about the relationship between visible foliar injury and the growth or vitality of sensitive plant species.

- Responses of eight tree species to the isolated effects of ground-level ozone exposures were simulated, and ranked in order from most to least sensitive to growth and species composition impacts:

  White ash>Basswood=Chestnut oak>Red maple>Yellow poplar>Black cherry=Red oak>Sugar maple.

- Simulations suggested that white ash is more sensitive to growth and species composition impacts than other species, both as an individual and as a component of a forest stand. Ambient ground-level ozone exposure caused an estimated 1% decrease in total growth of white ash, a long-lived species, over the three year simulation period.

Acidic Deposition

Sulfur retention in watershed soils reduces the potential for the acidification of surface waters because it decreases the mobility of sulfate. However, as the finite adsorption capacity of soils is exhausted, sulfate concentration can increase in soil waters and surface waters, potentially contributing to greater acidification. Based on published out-of-park research, it is unlikely that deciduous forest vegetation in the park has experienced sufficiently high deposition of sulfur or nitrogen to cause adverse acidification impacts, although high elevation and isolated coniferous forest areas may be more sensitive.

- The park's recently observed total (wet + dry) nitrogen deposition rates of close to 8 kilograms/hectare/year (kg/ha/yr) are approaching the 10 kg/ha/yr levels observed elsewhere to often be associated with nitrate leaching (an indicator of nitrogen saturation).

- Data from the 2000 soil survey of 14 park watersheds indicated that median base saturation (a reflection of soil acid-base status) was less than 10% for mineral soils associated with siliciclastic bedrock and less than about 14% for mineral soils associated with granitic bedrock in the park. This measure of watershed soil acid-base status is related to the stream's acid neutralizing capacity (ANC). All park watersheds that were characterized by soil base saturation less than about 14% had average streamwater ANC less than 100 microequivalents per liter (μeq/L). Watersheds that had higher soil base saturation were dominated by the basaltic bedrock type and had average streamwater ANC greater than 100 μeq/L.

Aquatic Ecosystem Status and Trends

The acid-base status of the park's streamwater chemistry is closely related to the characteristics of bedrock geology and soils. The park has three major geologic types underlain by siliciclastic (quartzite and sandstone), granitic, and basaltic bedrock. Each of these bedrock types underlies about one-third of the park area. Siliciclastic sites have the greatest sensitivity to acidification, while granitic sites have moderate sensitivity and basaltic sites have low sensitivity. Sulfur is the primary determinant of precipitation acidity and sulfate is the dominant acid anion associated with acidic streams, both in the central Appalachian Mountains region and within the park. Sulfur deposition has acidified park streams and affected in-stream biota, particularly in watersheds dominated by siliciclastic bedrock types that give rise to soils with low base saturation and relatively low sulfur adsorption, and to streams with low ANC. In the absence of severe disturbance such as forest defoliation by the gypsy moth, nitrogen is generally tightly cycled within park watersheds and does not contribute significantly toward streamwater acidification.

- Of the 14 park streams modeled for this assessment, none had simulated pre-industrial streamwater ANC less than 50 μeq/L, suggesting that these streams may have supported a greater variety of aquatic fauna.

- Almost half of the siliciclastic streams in a 1992 in-park survey of small subwatersheds were chronically acidic (ANC < 0 μeq/L) in which lethal effects on brook trout are probable. The balance of siliciclastic streams had ANC in the episodically acidic range (having chronic ANC between 0 and 20 μeq/L) in which sub-lethal or lethal effects are possible. Many of the streams associated with granitic bedrock in this survey were in the indeterminate ANC range (20-50 μeq/L) for brook trout. In contrast, the streams associated with basaltic bedrock had relatively high ANC values that were well within the suitable range for brook trout. These thresholds were developed for brook trout, which is considered the most acid tolerant fish species in the park. Species which are more acid-sensitive, such as blacknose dace and some mayfly species, likely have higher suitable ANC ranges than brook trout. Generally, ANC values greater than 20 to 50 μeq/L should support greater diversity and larger populations of aquatic fauna.

- Episodic acidification of park streams can be attributed to acidic deposition and natural processes, and it is superimposed on baseflow chemistry that is more acidic than pre-industrial conditions. Episodic ANC values are generally about 20% lower than baseflow values.

- Acidic episodes in low ANC park streams killed young brook trout and adult blacknose dace in field bioassays.

- Modeling results suggested that park streams that occur on siliciclastic bedrock have generally lost one or two species, and some streams may have lost up to four species, of fish in response to acidic deposition.

- Low ANC park streams generally have lower fish species richness, lower population density, poorer blacknose dace condition, fewer age classes, smaller sizes, and lower field bioassay survival than higher ANC streams.

- Higher ANC streams generally have greater numbers of families and numbers of individuals in each of three important benthic insect orders: mayflies (Ephemeroptera), stoneflies (Plecoptera), and caddisflies (Trichoptera) than low-ANC streams.

- Park streamwater chemistry is showing signs of ANC recovery in response to decreased sulfur deposition, whereas streamwater chemistry within the larger western Virginia region is not. Recent changes in both streamwater sulfate concentrations and ANC are generally smaller than in the northeastern United States, are confounded by seasonal differences, and in many cases are not statistically significant.

- Most park streams do not show evidence of ANC recovery in the winter season when the brook trout is present in its early, more acid-sensitive life stages.

Future Conditions and Prognosis for Recovery

Visibility

- Future improvements in annual average visibility projected to result from the emissions control scenarios ranged from 13% to 38% for Scenarios 2 through 4.

- For the summer season, the degree of needed visibility improvement to restore estimated natural background conditions at the park is nearly 85%. Implementation of the most stringent emissions control scenario (4) was forecasted to achieve a 52.4% improvement in average summer-time visibility at the park.

Terrestrial Ecosystems

- 1997 through 1999 ambient ground-level ozone exposures were projected to cause a 50% decrease in white ash species composition in chestnut oak forests projected over the 100-year simulation period.

- Ground-level ozone exposures greater than ambient levels were projected to cause less than 10% decrease in white ash and yellow poplar species composition in cove hardwood forests over 100 years.

- Ground-level ozone exposure scenarios were projected to cause 0 to 3% decrease in growth or species in yellow poplar forests composition over 100 years.

- Model results suggested that the isolated effects of ground-level ozone on growth and composition of park forests should diminish under Scenarios 2 through 4.

- Foliar injury on sensitive vegetation that occurs at lower ground-level ozone exposures (i.e., 10-15 ppm-hr SUM06) should diminish as a forest stress factor under Scenarios 2 through 4. Foliar injury is projected to be rare under Scenario 4, which assumes more than 50% reduction in ozone exposure.

- Modeling results suggested that ground-level ozone exposures about 15% less than 1997 through 1999 ambient levels should protect against isolated changes in white ash growth and species composition in the park's forests.

Aquatic Ecosystems

Model projections of future streamwater ANC in streams on siliciclastic bedrock ranged from simulated changes less than 10 to greater than 40 μeq/L for scenarios 1 through 4.

- In response to substantial reductions in sulfur deposition (Scenario 4), model projections for the year 2100 suggested that park streams on siliciclastic bedrock would likely experience increases of one to two species of fish, improved suitability for brook trout, and improved condition of blacknose dace. However, none of these streams are projected to fully recover the estimated number of fish species lost in the past in response to acidic deposition.

- Levels of continuous future sulfur deposition that were simulated to cause streamwater ANC to change to three specified critical levels (0, 20 and 50 μeq/l) ranged from less than zero (not attainable) to several hundred kg/ha/yr, depending on the site, ANC endpoint, and evaluation year. The specified critical levels correspond to general aquatic fauna response categories.

- Modeled streams on siliciclastic bedrock showed critical sulfur deposition loads ranging from 9 to 15 kg/ha/yr in order to protect against chronic acidity (ANC less than 0) in the year 2100. Lethal effects on brook trout are probable at ANC less than 0.

- Modeled streams on siliciclastic bedrock showed critical sulfur deposition loads ranging from 6 to 11 kg/ha/yr in order to protect against acidification to ANC of 20 μeq/L in the year 2100. Sub-lethal or lethal episodic effects on brook trout are possible at ANC 0 to 20 μeq/L.

- Modeled streams on siliciclastic bedrock showed critical sulfur deposition loads ranging from less than 0 (not attainable in one modeled stream) to 6 kg/ha/yr to protect against acidification to ANC of 50 in the year 2100. Streams having ANC above 50 μeq/L generally support greater diversity and populations of aquatic fauna than do lower ANC streams.

Conclusions

This assessment reveals that the park's visibility and most sensitive aquatic ecosystems have been degraded by human-made air pollution, although there is some evidence of recent improvement, presumably as a result of Clean Air Act implementation**.** Full recovery of the park's estimated natural visibility conditions and acid-base chemistry of the most sensitive streams would not occur under any of the four emissions control scenarios, although varying degrees of progress would be made. Implementation of the 1990 Clean Air Act Amendments (Scenario 2) should make substantial progress toward or possibly achieve protecting park forests from the isolated effects of ground-level ozone on tree growth, forest growth, and changes in forest species composition. However, model simulations of isolated effects may underestimate ground-level ozone forest effects, since ozone does not act alone. The park's air quality and related values are primarily influenced by emission sources in Great Lakes States, Mid-Atlantic States, Southeastern States, and several key source subregions that transcend state boundaries. These states and subregions can contribute the most through collaborative, intra- and inter-regional efforts toward restoring and protecting clean air, clear views, and healthy aquatic and terrestrial ecosystems in Shenandoah National Park.